SD7332S100398

Method for Forming Permanent Magnets with Different Polarities for Use in Microelectromechanical Devices

INVENTORS:

Alexander W. Roesler
20 Vallecitos Loop
Tijeras, New Mexico 87059

Todd R. Christenson
1621 Speakman, S.E.
Albuquerque, New Mexico 87123

Express #: EV332387275US

Method for Forming Permanent Magnets with Different Polarities for Use in Microelectromechanical Devices

GOVERNMENT RIGHTS

This invention was made with Government support under Contract No. DE-AC04-94AL85000 awarded by the U.S. Department of Energy. The Government has certain rights in the invention.

CROSS REFERENCE TO RELATED APPLICATIONS

This application is related to an application entitled "Microelectromechanical Power Generator and Vibration Sensor" which is being filed of even date with Attorney Docket No. SD7333S100399.

FIELD OF THE INVENTION

The present invention relates in general to rare-earth permanent magnets, and in particular to a method for forming a plurality of rare-earth permanent magnets having two different polarities (i.e. north-south magnetic pole alignments) with applications for use in forming permanent-magnet microelectromechanical (MEM) devices.

BACKGROUND OF THE INVENTION

Microelectromechanical (MEM) fabrication technologies such as surface and bulk micromachining and LIGA (an acronym based on the first letters for the German words for lithography, electroplating and injection molding) have been extensively developed in recent years to form many different types of microsystems and microsensors. For certain uses, these microsystems and microsensors can include

one or more permanent magnets. Current fabrication technologies result in each permanent magnet having the same magnetic pole alignment unless piece-part assembly is used to insert pre-magnetized permanent magnets into a device. What is needed is a method of forming a plurality of permanent magnets in an unmagnetized state and then magnetizing them with a predetermined north-south magnetic pole alignment.

The present invention provides an advance in the art by addressing the above need and providing a method based on thermally-assisted magnetic field switching which can be used to switch the north-south magnetic pole alignment of certain of the permanent magnets to an opposite polarity while not changing the north-south magnetic pole alignment for the remainder of the permanent magnets.

The present invention can be used to form MEM devices having an alternating north-south magnetic pole alignment for different types of applications including mechanical energy harvesting to generate electrical power, for vibration sensing, for acceleration or impact sensing, etc.

The present invention can also be used to form permanent magnet direct current (dc) motors which can be fabricated, for example, by LIGA.

These and other advantages of the present invention will become evident to those skilled in the art.

SUMMARY OF THE INVENTION

The present invention relates to a method for forming a plurality of permanent magnets with two different north-south magnetic pole alignments that comprises initially magnetizing each permanent magnet with the same north-south magnetic pole alignment, and then switching the north-south magnetic pole alignment of a portion of the permanent magnets. This switching can be done by temporarily heating the portion to a temperature in the range of 0 - 200 °C below a Curie temperature of

the permanent magnets making up the portion, with the heating reducing a first threshold for switching of the north-south magnetic pole alignment of that portion of the permanent magnets. With the portion of permanent magnets being heated as described above, the portion is exposed to a magnetic field which is directed oppositely to the initial north-south magnetic pole alignment, with the oppositely-directed magnetic field having a magnetic field strength which is above the first threshold for switching the alignment of the portion of the permanent magnets, but below a second threshold for switching the alignment of a remainder of the permanent magnets.

The permanent magnets preferably comprise rare-earth permanent magnets although the methods of the present invention are also applicable to other types of permanent magnets (e.g. iron-platinum or iron-chromium-cobalt permanent magnets). The portion of the permanent magnets being switched can comprise neodymium-iron-boron (NdFeB) permanent magnets; and the remainder of the permanent magnets not being switched can comprise samarium-cobalt (SmCo) permanent magnets. The permanent magnets can be located on or within a substrate, arranged either side-by-side or in a two-dimensional array. In a side-by-side arrangement, every other permanent magnet can be a part of the portion whose polarity is to be switched using the method of the present invention. In a two-dimensional array, the portion of the permanent magnets whose polarity is to be switched can comprise every other row of permanent magnets in the two-dimensional array.

In certain embodiments of the present invention, the oppositely-directed magnetic field can be produced in part or entirely by the SmCo permanent magnets. When the SmCo permanent magnets are used to generate the oppositely-directed magnetic field, a soft-magnetic plate can be located proximate to one or both poles of the SmCo permanent magnets for enhancing the oppositely-directed magnetic field.

(e.g. by channeling the oppositely-directed magnetic field into the portion of the permanent magnets whose polarity is to be switched).

The step of exposing each permanent magnet within the portion of the permanent magnets whose polarity is to be switched can comprise providing an external magnetic field for generating the oppositely-directed magnetic field. The external magnetic field can be concentrated at the location of each permanent magnet within the portion of the permanent magnets whose polarity is to be switched. This can be done, for example, by locating a soft-magnetic material proximate to at least one pole of each permanent magnet in the portion of the permanent magnets whose polarity is to be switched. As an example, the soft-magnetic material can be provided on or within a plate formed from a non-magnetic material which is located proximate to one or both poles of each permanent magnet in the portion whose polarity is to be switched. As another example, a plate formed of the soft-magnetic material can be located proximate to one or both poles of each permanent magnet within the portion whose polarity is to be switched. This soft-magnetic plate can further be shaped to provide the oppositely-directed magnetic field to the portion of the permanent magnets whose polarity is to be switched while at the same time directing the external magnetic field into the remainder of the permanent magnets, whose polarity is not to be switched, in a direction substantially equal to the north-south magnetic field alignment thereof. This can be done, for example, by generating the external magnetic field using an electrical current passing through a meandering electrical conductor disposed within a plurality of elongate slots formed in the soft-magnetic plate.

The present invention further relates to a method for forming a plurality of permanent magnets with two opposite north-south magnetic pole alignments which comprises providing a first set of the permanent magnets having a first Curie temperature, providing a second set of the permanent magnets having a second

Curie temperature lower than the first Curie temperature, magnetizing the first and second sets with the same north-south magnetic pole alignment and switching the north-south magnetic pole alignment of the second set of the permanent magnets. The first Curie temperature can be, for example, in the range of 700 - 800 °C, and the second Curie temperature can be, for example, in the range of 300 - 400 °C. The switching step can be performed by temporarily heating each permanent magnet in the second set to a temperature in the range of 0 - 200 °C below the second Curie temperature in the presence of a magnetic field which is oppositely directed with respect to the north-south magnetic pole alignment of the first and second sets of the permanent magnets, with the magnetic field being above a first threshold for switching the north-south magnetic pole alignment of the second set of the permanent magnets at the temperature to which the second set of the permanent magnets are temporarily heated and below a second threshold for switching the north-south magnetic pole alignment of the first set of the permanent magnets.

The first set of the permanent magnets can comprise samarium-cobalt (SmCo) permanent magnets; and the second set of the permanent magnets can comprise neodymium-iron-boron (NdFeB) permanent magnets. The first and second sets of the permanent magnets can be provided on or within a substrate (e.g. in an alternating arrangement, or as an array with certain rows in the array being formed from the second set of the permanent magnets and other rows in the array being formed from the first set of the permanent magnets).

In some embodiments of the present invention, the oppositely-directed magnetic field can be produced, at least in part, by the first set of the permanent magnets. This can be done, for example, by locating a soft-magnetic plate proximate to at least one pole of each permanent magnet in the first set of the permanent magnets for enhancing the oppositely-directed magnetic field.

In other embodiments of the present invention, the oppositely-directed

magnetic field can comprise an external magnetic field. In these embodiments, the external magnetic field can be concentrated at the location of each permanent magnet in the second set of the permanent magnets. This can be done, for example, by locating a soft-magnetic material proximate one or both poles of each permanent magnet in the second set of the permanent magnets. The soft-magnetic material can be provided on or within a plate formed from a non-magnetic material, or alternately provided as a soft-magnetic plate.

The present invention also relates to a method for forming a first set of permanent magnets with a north-south magnetic pole alignment and a second set of permanent magnets with an opposite north-south magnetic pole alignment. This method comprises forming the first set of permanent magnets on or within a substrate in an unmagnetized state, with the first set of permanent magnets having a first Curie temperature, forming the second set of permanent magnets on or within the substrate in an unmagnetized state, with the second set of permanent magnets having a second Curie temperature lower than the first Curie temperature, magnetizing the first and second sets of permanent magnets with the same north-south magnetic pole alignment, and then switching the north-south magnetic pole alignment of the second set of the permanent magnets. The switching step can be performed by heating the first and second sets of permanent magnets to a temperature in a range of 0 - 200 °C below the second Curie temperature, exposing the first and second sets of permanent magnets to a magnetic field which is oppositely directed to the north-south magnetic pole alignment of the first set of permanent magnets, with the magnetic field being above a threshold for switching the north-south magnetic pole alignment of the second set of permanent magnets while at the same time being below another threshold for switching the north-south magnetic pole alignment of the first set of permanent magnets, and cooling the first and second sets of permanent magnets and thereby locking in an oppositely-directed

north-south magnetic pole alignment for the second set of permanent magnets. The first set of permanent magnets can comprise samarium-cobalt (SmCo) permanent magnets, and the second set of permanent magnets can comprise neodymium-iron-boron (NdFeB) permanent magnets. The cooling step can comprise cooling the first and second sets of permanent magnets down to room temperature.

The present invention further relates to a method for forming a plurality of permanent magnets with two different north-south magnetic pole alignments that comprises the steps of magnetizing each permanent magnet with the same north-south magnetic pole alignment, and switching the north-south magnetic pole alignment of a portion of the permanent magnets. The switching step can be performed by temporarily heating the portion of the permanent magnets to a temperature in the range of 0 - 100 °C above a Curie temperature thereof and below a Curie temperature for a remainder of the permanent magnets, thereby reducing a first threshold for switching of the north-south magnetic pole alignment of the portion of the permanent magnets, and exposing the portion of the permanent magnets to a magnetic field which is directed oppositely to the north-south magnetic pole alignment of the permanent magnets, with the oppositely-directed magnetic field having a magnetic field strength which is above the first threshold for switching the alignment of the portion of the permanent magnets, while being below a second threshold for switching of the north-south magnetic pole alignment for the remainder of the permanent magnets. The portion of the permanent magnets can comprise neodymium-iron-boron (NdFeB) permanent magnets, and the remainder of the permanent magnets can comprise samarium-cobalt (SmCo) permanent magnets.

Additional advantages and novel features of the invention will become apparent to those skilled in the art upon examination of the following detailed description thereof when considered in conjunction with the accompanying drawings. The advantages of the invention can be realized and attained by means of the

instrumentalities and combinations particularly pointed out in the appended claims.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings, which are incorporated into and form a part of the specification, illustrate several aspects of the present invention and, together with the description, serve to explain the principles of the invention. The drawings are only for the purpose of illustrating preferred embodiments of the invention and are not to be construed as limiting the invention. In the drawings:

Fig. 1 shows a schematic plan view of a first example of a MEM apparatus, with the MEM apparatus having a side-by-side arrangement of permanent magnets with an alternating north-south magnetic pole alignment and being useable as an electrical power generator, as a vibration sensor or as a flux compression generator.

Fig. 2 shows a schematic cross-section view of the MEM apparatus of Fig. 1 along the section line 1 - 1 in Fig. 1.

Fig. 3 shows an enlarged cross-section view of a portion of the MEM apparatus of Figs. 1 and 2 to illustrate lines of magnetic flux ϕ coupled from the permanent magnets to an underlying meandering electrical pickup to produce an electrical voltage therein in response to a vibration-induced movement of the permanent magnets and supporting shuttle.

Fig. 4 shows a schematic plan view of the apparatus of Fig. 1 with the shuttle and permanent magnets removed to show the underlying meandering electrical pickup.

Figs. 5A - 5K illustrate fabrication of the MEM apparatus of Fig. 1 using a series of LIGA process steps.

Fig. 6 shows a schematic cross-section view of a second example of the MEM having a side-by-side arrangement of permanent magnets with an alternating north-south magnetic pole alignment.

Fig. 7 shows an enlarged partial cross-section view of a portion of the MEM apparatus of Fig. 6 to show details therein including a channeling of the lines of magnetic flux ϕ produced by a soft-magnetic layer provided between each meandering electrical pickup and a supporting substrate.

Fig. 8 shows a schematic plan view of a third example of a MEM apparatus having a two-dimensional array of permanent magnets formed with alternating rows in the array having permanent magnets with opposite north-south magnetic pole alignments.

Fig. 9 shows a schematic plan view of the meandering electrical pickup formed on one substrate which can be attached to a second substrate to form the MEM apparatus of Fig. 8.

Figs. 10A - 10C show schematic cross-section views to illustrate a method according to the present invention for producing a plurality of permanent magnets having an alternating north-south magnetic pole alignment.

Figs. 11A - 11C schematically illustrate in cross-section view another method according to the present invention for producing a plurality of permanent magnets having an alternating north-south magnetic pole alignment.

DETAILED DESCRIPTION OF THE INVENTION

Referring to Fig. 1, there is shown a first example of a microelectromechanical (MEM) apparatus 10 which can be used as an electrical power generator, a vibration sensor, or a flux compression generator. In each case, the MEM apparatus 10 produces a voltage in response to movement of a plurality of permanent magnets therein, with the movement of the permanent magnets being in response to vibration, acceleration or impact.

The MEM apparatus 10 in Fig. 1 comprises a substrate 12 whereon a meandering electrical pickup 14 is disposed. A moveable shuttle 16 is suspended

over the meandering electrical pickup 14, with the shuttle 16 holding a plurality of permanent magnets 18 and 18' arranged side-by-side in a plane with an alternating north-south magnetic pole alignment. The phrase “north-south magnetic pole alignment” defines a line running between a north pole and a south pole of a particular permanent magnet 18 or 18' and further indicates at which end of that line the north pole and south pole are located. Thus, an alternating north-south magnetic pole alignment refers to one permanent magnet 18 having its north pole in a particular direction and an adjacent permanent magnet 18' having its north pole in an opposite direction and so on. In Fig. 2, a vertical arrow is used to indicate the north-south magnetic pole alignment, with the arrow pointing toward the north pole for each magnet 18 and 18'.

In Fig. 1, the permanent magnets 18 and 18' are spaced apart by a predetermined distance which can be about the same as a spacing between turns of the meandering electrical pickup 14, or a multiple thereof. The phrase “turn” used in reference to the meandering electrical pickup 14 refers to a segment of the meandering electrical pickup 14 formed from a pair of relatively long electrical conductors arranged in a direction substantially perpendicular to a direction of motion of the shuttle 16 as indicated by the double-headed arrow in Fig. 1 and a pair of relatively short electrical conductors arranged substantially parallel to the direction of motion of the shuttle 16.

In the example of Fig. 1, the shuttle 16 is suspended above the substrate 12 by a plurality of springs 20 which can be folded to save space. One end of each spring 20 is attached to the shuttle 16, and the other end of each spring 20 can be attached to a support 22 on the substrate 12.

The shuttle 16 is suspended for movement in response to vibrations 100 from an external vibration source 110 as shown in Fig. 2, with the vibrations 100 being operatively coupled to the shuttle 16 to move the shuttle 16 back and forth in a

direction substantially parallel to the substrate 12 as indicated by the double-headed arrow. Although the external vibration source 110 is shown located above the MEM apparatus 10 in Fig. 2, the vibration source 110 can be located in any position relative to the MEM apparatus 10 which results in movement of the shuttle 16 in the direction indicated by the double-headed arrow. Generally, when possible the MEM apparatus 10 will be oriented with respect to the external vibration source 110 so as to produce a maximum extent of travel of the shuttle 16 in the back-and-forth direction indicated by the double-headed arrow in Fig. 2.

The external vibration source 110 can be a stationary machine wherein moving parts produce a vibration 100 (e.g. a combustion engine) or wherein external forces produce the vibration 100 (e.g. a bridge vibrating from traffic or wind; a building vibrating from wind or an earthquake; etc.). The external vibration source 110 can also be a moveable machine (e.g. a car, truck, airplane etc.) with a combination of internal (e.g. an engine) and external (e.g. a road, wind or both) sources 110 of vibration. Vibrations 100 from the source 110 can be coupled into the MEM apparatus 10 by direct contact (e.g. by attaching the MEM apparatus to the vibration source 110 or to anything mechanically connected to the vibration source 110) or by indirect contact (e.g. by coupling of the vibrations 100 through the air as sound, or through water, earth, etc.).

The MEM apparatus 10 of Fig. 1, when used as an electrical power generator can be used to generate an alternating-current (ac) voltage which can be rectified and converted to a direct-current (dc) voltage for use in powering integrated circuitry, sensors or other MEM devices which can be formed on a common substrate 12 together with the apparatus 10, or located in a common package therewith. The MEM apparatus 10 can also be used as a vibration sensor to generate an electrical output voltage to indicate the presence and magnitude of external vibrations coupled into the apparatus 10. The MEM apparatus 10 can further be used as a flux compression

generator to generate a large voltage pulse in response to a rapid acceleration or deceleration. Such a large voltage pulse could be used, for example, to trigger an automobile airbag in response to a collision.

As the shuttle 16 in the MEM apparatus 10 is urged to move in response to vibrations from the external source 110 coupled to the apparatus 10, the various permanent magnets 18 and 18' in the shuttle 16 move relative to the turns of the meandering electrical pickup 14. This motion of the permanent magnets 18 and 18' induces an electrical voltage, V, in the pickup 14 which is proportional to a rate of change of a magnetic flux, ϕ, produced by according to Faraday's Law:

$$V = -N\frac{d\phi}{dt} = -N\frac{d\phi}{dx}\frac{dx}{dt} = -N\frac{d\phi}{dx}v \qquad \text{Eq. 1}$$

In Equation 1 above, N is the number of turns in the meandering electrical pickup 14, $d\phi/dx$ is the rate of change in the magnetic flux ϕ with distance x of the shuttle 16 and v is a velocity of movement of the shuttle 16 which is related to the frequency of the vibrations (e.g. a few Hertz to a few kiloHertz) responsible for movement of the shuttle 16. By providing the plurality of permanent magnets 18 and 18' with an alternating north-south magnetic pole alignment as shown in the schematic cross-section view of Fig. 2, the rate of change of the magnetic flux with distance (i.e. $d\phi/dx$) can be maximized since a full cycle in magnetic flux variation will occur each time the shuttle 16 moves over a distance equal to the spacing between each adjacent pair of the permanent magnets 18 and 18'.

Figure 3 is an enlarged partial view of a portion of the MEM apparatus 10 in Fig. 2 to show lines of the magnetic flux ϕ (indicated by the closed paths with an arrow pointing towards a north pole of the magnet, and with a south pole of the magnet being in the opposite direction) which are produced by the permanent magnets 18 and 18' for coupling to the meandering electrical pickup 14 for generating the electrical voltage, V, therein. Although the arrows in Figs. 2 and 3 are vertically

oriented to show a north-south magnetic pole alignment that is substantially perpendicular to the plane of the substrate 12, those skilled in the art will understand that the north-south magnetic pole alignment can also be substantially parallel to the plane of the substrate 12, or at any angle relative to the substrate 12 so long as the lines of the magnetic flux ϕ pass around the turns of the meandering electrical pickup 14 as shown in Fig. 3.

In the example of Fig. 1, the springs 20 can be made with a high aspect ratio of height to width (e.g. about 5:1 to 10:1 or more) so that the springs 20 will allow the shuttle 16 and attached magnets 18 and 18' to move relatively freely in a direction substantially parallel to the surface of the substrate 12 in the direction shown by the double-headed arrow in Figs. 1 and 2 while resisting motion in a direction substantially perpendicular to the surface of the substrate 12. The supports 22 also resist motion in the plane of the substrate in a direction normal to that of the double-headed arrow in Fig. 1. The shuttle 16 can have lateral dimensions of, for example, 1 - 3 centimeters on a side and can be, for example, 50 - 500 μm thick, with the springs 20 generally being the same thickness of the shuttle 16 and being, for example, 25 μm wide.

Figure 4 shows a schematic plan view of the MEM apparatus 10 of Fig. 1 with the shuttle 16 removed to show the underlying meandering electrical pickup 14. The meandering electrical pickup 14 can comprise an electrical conductor having lateral dimensions of, for example, 1 - 10 μm thickness and 10 - 25 μm width, with each turn of the pickup 14 being spaced from an adjacent turn by, for example, 50 μm. The meandering electrical pickup 14 can be connected to a contact pad 24 at either end thereof as shown in Fig. 4 for attaching external wires (not shown) to the MEM apparatus 10. In other embodiments of the MEM apparatus 10, a plurality of meandering electrical pickups 14 can be formed on the substrate 12 in a nested (i.e. interleaved or stacked) arrangement, with the nested pickups 14 being electrically

interconnected in series to provide an increased voltage, or being interconnected in parallel to provide an increased current.

The MEM apparatus 10 of Fig. 1 can be formed as described hereinafter with reference to Figs. 5A - 5K.

In Figs. 5A and 5B, the meandering electrical pickup 14 can be formed on the substrate 12. The shuttle 16, permanent magnets 18 and 18', springs 20 and supports 22 in this example of the MEM apparatus 10 are formed separately and subsequently attached to the substrate 12 to complete the MEM apparatus 10.

When the substrate 12 is electrically insulating (e.g. comprising glass, ceramic, fused silica, quartz, printed-circuit board material, etc.), the pickup 14 can be formed directly on the substrate 12. Alternately, when the substrate 12 is electrically conducting (e.g. comprising a metal, metal alloy or a semiconductor material such as silicon), an electrically-insulating layer (e.g. comprising silicon dioxide, silicon nitride, aluminum oxide, a polymer, a silicate glass or a spin-on glass) can be blanket deposited over the substrate 12 to electrically insulate the pickup 14 from the substrate 12.

In Fig. 5A, an electrically-conducting layer 26 (e.g. comprising a metal or metal alloy which further comprises copper, aluminum, gold, silver, platinum, palladium, etc.; or comprising a doped semiconductor such as doped polycrystalline silicon) can be provided as a full-surface layer 26 covering the substrate 12 with a thickness of, for example, 10 μm. The electrically-conductive layer 26 can then be patterned by etching as shown in Fig. 5B to form the meandering electrical pickup 14 and contact pads 24 on the substrate 12.

As an example, to form the meandering electrical pickup 14 on a substrate 12 comprising a printed-circuit board, a conventional printed-circuit board can be obtained with a full-surface layer 26 of copper about 10 μm thick on at least one side thereof. A photoresist mask can then be photolithographically defined over areas of

the copper layer 26 that are to be retained and used for forming the meandering electrical pickup 14 and contact pads 24; and the remainder of the copper layer 26 can be removed using a conventional printed-circuit board etchant solution.

As another example, when the substrate 12 comprises glass or quartz, an electrically-conductive layer 26 of a metal, metal alloy or doped polycrystalline silicon (e.g. doped to about 10^{18} cm^{-3} or more with boron or phosphorous) can be blanket deposited over the substrate 12 as shown in Fig. 5A using evaporation, sputtering, or chemical vapor deposition. In some instances a thin (e.g. 200 - 1000 nm) seed layer can be initially blanked deposited over the substrate 12; and then a thicker (e.g. up to 10 µm) electrically-conductive layer can be plated over the seed layer to build-up a predetermined thickness of the electrically-conductive layer 26. A photolithographically-defined mask can then be formed over the electrically-conductive layer 26 using well-known integrated circuit processing technology to define the shape of the meandering electrical pickup 14 and contact pads 24. The remainder of the electrically-conductive layer 26 not protected by the mask can then be etched away as shown in Fig. 5B.

As yet another example, a low-temperature co-fired ceramic (LTCC) substrate 12 in a "green" state can be provided with the meandering electrical pickup 14 and the contact pads 24 being formed thereon by screen printing a metal paste (e.g. comprising silver). This substrate 12 can then be heated at an elevated temperature (e.g. ≥ 800 °C) to co-fire the ceramic and sinter the metal paste, and also to remove any organic binders or plasticizers used in the metal paste.

In Figs. 5C - 5J, the shuttle 16, permanent magnets 18 and 18', springs 20 and supports 22 can be formed separately on a sacrificial substrate 28 by a series of LIGA process steps as described hereinafter.

In Fig. 5C, a sacrificial substrate 28 can be provided with a sacrificial layer 30 formed thereon. As an example, the sacrificial substrate 28 can comprise alumina,

nickel or silicon; and the sacrificial layer 30 can comprise copper about 1 μm thick which has been deposited or electroplated over the entire surface of the substrate 28. As another example, the sacrificial substrate 28 can comprise copper, nickel or silicon; and the sacrificial layer 30 can comprise an electrically-conductive polymer such as polymethymethacrylate (PMMA) loaded with 60 - 70 wt-% silver particles.

In Fig. 5D, a mask 32 can be formed over the sacrificial substrate 28. The mask 32 can comprise, for example, PMMA which can be exposed by deep x-ray lithography (e.g. using a synchrotron deep x-ray source) and then developed to define a pattern for the mask 32, with openings 34 in the mask 32 at the locations wherein the shuttle 16, springs 20 and supports 22 are to be formed. The mask 32 preferably has a thickness that is substantially equal to or greater than the thickness of the various elements 16, 20 and 22 being formed on the sacrificial substrate 28. As an example, the thickness of the mask 32 can be in the range of 50 - 500 μm. The width of the openings 34 for the shuttle 16 can be, for example, 50 - 100 μm; and the width of the openings 34 for the springs 20 can be about 25 μm wide, for example.

In Fig. 5E, a soft-magnetic material 36 such as nickel (Ni), nickel-iron (NiFe), iron-cobalt (FeCo), or nickel-iron-cobalt (NiFeCo) can be electroplated to fill in the openings 34 in the mask 32 for use in forming the shuttle 16, the springs 20 and the supports 22. In this example of the MEM apparatus 10, the soft-magnetic material will also be used to form the permanent magnets 18'. In other embodiments of the MEM apparatus 10, a non-magnetic material can be substituted for the soft-magnetic material 36 in forming the shuttle 16, springs 20 and supports 22.

In Fig. 5F, the mask 32 can be removed by with a solvent (e.g. acetone) to leave the soft-magnetic material 36 in place on the substrate, with portions of the soft-magnetic material 36 being separated by slots 40. In Fig. 5G, a non-magnetic material 38 (e.g. tungsten, platinum, copper, beryllium-copper, etc.) can be electroplated over the soft-magnetic material 36 to a layer thickness of, for example

25 μm. Electroplating of the soft-magnetic material 36 at the bottom of the slots 40 can be prevented by not completely removing the mask 32 from the bottom of the slots 40, or alternately by depositing a thin electrically-insulating layer (e.g. photoresist) at this location. The non-magnetic material 38 is advantageous for extending the lines of magnetic flux ϕ from the permanent magnets 18 down beyond the shuttle 16 and into the vicinity of the meandering electrical pickup 14 as shown in Fig. 3. In Fig. 5H, a portion of the non-magnetic material 38 extending above the soft-magnetic material 38 can be removed by a mechanical or chemical-mechanical polishing step.

In the event that the soft-magnetic material 38 is deposited at the bottom of the slots 40, this material 38 can be removed by a further polishing step after the shuttle 16 with the attached permanent magnets 18 and 18', springs 20 and supports 22 has been formed as a shuttle assembly 44 and removed from the sacrificial substrate 28 by etching or dissolving away the sacrificial layer 30. For this further polishing step, the shuttle assembly 44 can be temporarily attached upside down to a support substrate.

In Fig. 5I, a rare-earth magnetic material 42 can be deposited to fill up each slot 40 between the soft-magnetic material 36. The rare-earth magnetic material 42 can comprise neodymium-iron-boron (NdFeB) or samarium-cobalt (SmCo) rapidly-quenched powder with a sub-micron grain size. The rare-earth magnetic material 42 in an unmagnetized state can be mixed with a binder material (e.g. epoxy or a polymer) and then filled into the slots 40. This can be done by many different well-known processes including calendering, doctor-blading, pressing, squeegeeing, injection molding etc. as disclosed by Christenson in U.S. Patent No. 6,375,759 which is incorporated herein by reference.

Once in place, the rare-earth magnetic material 42 can then be hardened (e.g. by a curing, sintering or thermo-setting step). Any of the rare-earth magnetic material

42 extending upward beyond the height of the soft-magnetic material 36 can then be removed by another polishing step. The rare-earth magnetic material 42 can be magnetized to saturation using a high magnetic field (e.g. a pulsed magnetic field). This forms a plurality of rare-earth permanent magnets 18 each having a north-south magnetic pole alignment which is directed substantially perpendicular to the substrate 28 as indicated by the upward-pointing arrows in Fig. 5J. An energy product BH for each rare-earth permanent magnet 18 can be, for example, about 10 MegaGauss-Oersted (MGOe).

The soft-magnetic material 36 adjacent to each rare-earth permanent magnet 18 is magnetized by the lines of magnetic flux ϕ from the rare-earth permanent magnets 18 which pass through the soft-magnetic material 36 in a direction (indicated by the downward-pointing arrows in Fig. 5J, and as shown in Fig. 3) that is opposite that of the adjacent rare-earth permanent magnets 18. Due to the continued presence of the rare-earth permanent magnets 18 located in the MEM apparatus 10, the soft-magnetic material 36 remains in a magnetized state and is considered herein as forming the oppositely-directed permanent magnets 18'. The net result in Fig. 5J is a series of permanent magnets 18 and 18' having an alternating north-south magnetic pole alignment with a magnetic flux reversal on a distance scale substantially equal to the distance between adjacent turns of the meandering electrical pickup 14 (see also Fig. 3). This spacing can be about 50 - 100 μm, for example.

In other embodiments of the MEM apparatus 10, pre-formed rare-earth permanent magnets 18 and 18' can be pressed into the slots 40 or attached therein by an adhesive (e.g. epoxy), with the permanent magnets 18 and 18' having an alternating north-south magnetic pole alignment. In yet other embodiments of the MEM apparatus 10, a plurality of permanent magnets can be formed in place with an alternating north-south magnetic pole alignment as will be described hereinafter.

After the shuttle 16 with the attached permanent magnets 18 and 18', springs 20 and supports 22 has been formed as an assembly 44 on the sacrificial substrate 28, this shuttle assembly 44 can be separated from the substrate 28 and attached to the substrate 12 as shown in Fig. 5K to form the MEM apparatus 10. The attachment of the shuttle assembly 44 to the substrate 12 can be performed either prior to or after removal of the sacrificial substrate 28 by using a selective etching or solvent dissolution step to remove the sacrificial layer 30 and thereby release the shuttle assembly 44 from the sacrificial substrate 28. Attachment of the shuttle assembly 44 to the substrate 28 via the support posts 22 can be made using a plurality of pins and/or screws, or alternately using solder, epoxy, or diffusion bonding, with the mode of attachment generally depending upon the exact composition of the substrate 12 and the material used for forming the supports 22. The spacing between the shuttle 16 and permanent magnets 18 and 18' and the meandering electrical pickup 14 in the completed MEM apparatus 10 can be, for example, 7 μm.

Since the generated electrical power scales up as the square of the voltage across the meandering electrical pickup 14 and hence as the square of the velocity, v, of the shuttle 16 from Equation 1, the generated electrical power can be substantially increased by operating the MEM apparatus 10 at a resonant frequency that is substantially equal to a dominant resonant frequency of a particular vibration environment (i.e. a particular vibration source 110). Operating at resonance maximizes the distance over which the shuttle 16 moves back and forth for each cycle of the dominant resonant frequency of the vibration 100 and thereby maximizes the velocity of the shuttle 16. The mass of the shuttle 16 and attached magnets 18 and 18' and a spring constant for the springs 20 can be selected so that the resonant frequency of the MEM apparatus 10 matches the dominant resonant frequency of the vibration environment. When the MEM apparatus 10 is used as a vibration sensor, matching the resonant frequency to the dominant resonant frequency of a particular

vibration 100 will increase the voltage generated across the pickup 14 which provides an output signal for the vibration sensor 10. It is expected that the MEM apparatus 10 will be capable of producing up to several milliWatts of electrical power when operating at resonance.

In some embodiments of the MEM apparatus 10, a plurality of meandering electrical pickups 14 can be stacked one upon the other with a thin (e.g. about 200 nm) layer of electrical insulation (e.g. silicon nitride, silicon dioxide, a silicate glass such as a TEOS-deposited silicate glass, a spin-on glass or a polymer) separating adjacent of the stacked pickups 14. Each stacked electrical pickup 14, which can have an electrical conductor that is, for example, 1 - 2 μm thick and a few μm wide, can be connected to a pair of contact pads 24 so that the pickups 14 can be externally wired in series or parallel to provide a predetermined level of voltage or current from the MEM apparatus 10. Alternately, electrical wiring can be provided on the substrate 12 to provide a predetermined series or parallel connection of the stacked pickups 14. The use of multiple stacked pickups 14 in a series configuration is advantageous for providing a higher output voltage than could be achieved using only a single meandering electrical pickup 14. In this way, it is expected that the output voltage can be increased to, for example, 5 - 10 volts which is sufficient to drive other integrated circuitry or MEM devices that can be provided on the same substrate 12. For optimal power transfer to a load, the electrical resistance of the meandering electrical pickup 14 can be matched to the resistance of the load.

In other embodiments of the MEM apparatus 10, a plurality of meandering electrical pickups 14 can be interleaved so that a plurality of turns are nested together. The nested turns can be interconnected in series to provide an increased output voltage. This can be done, for example, by forming a plurality of electrically-conductive vias to electrically connect each turn of the pickup 14 to an underlying interconnection layer which can be used to provide a series connection of the nested

turns.

Figure 6 shows a schematic cross-section view of a second example of the MEM apparatus 10 which can be fabricated in a manner similar to that described previously with reference to Figs. 5A - 5K except for having a second substrate 12' with a meandering electrical pickup 14' that is inverted over the shuttle assembly 44 and attached to the substrate 12 by a plurality of standoffs (not shown). In the example of Fig. 6, the direction of motion of the shuttle 16 due to a sensed vibration is indicated by the double-headed arrow. The provision of two meandering electrical pickups 14 and 14' in the apparatus 10 can double the generated electrical power and voltage. The generated electrical power can also be scaled up linearly with an overall area of the shuttle 16 and permanent magnets 18 and 18' and the meandering electrical pickups 14 and 14' when the dimensions and spacing of the permanent magnets 18 and 18' are fixed.

A substantial further increase in the generated electrical power and voltage can be provided in the MEM apparatus 10 of Fig. 6 by including a soft-magnetic layer 46 or 46' beneath each meandering electrical pickup 14 or 14' on the substrate 12 or 12'. The soft-magnetic layers 46 and 46' concentrate and channel the magnetic flux ϕ as shown in the enlarged partial cross-section view of Fig. 7 thereby increasing an electrical inductance of the meandering electrical pickup 14 by increasing the magnetic flux ϕ linking each turn in the pickup 14. This increased inductance of the pickup 14 allows a larger voltage V to be generated therein, thereby increasing the power generation efficiency of the MEM apparatus 10. Calculations show that the magnetic flux concentration provided by the soft-magnetic layers 46 and 46' in the MEM apparatus 10 of Figs. 6 and 7 can provide up to a three-fold increase in electrical power generation compared to the same device 10 without the soft-magnetic layers 46 and 46'.

In the example of Figs. 6 and 7, the soft-magnetic layers 46 and 46' can

comprise, for example, NiFe, FeCo, NiFeCo, iron-aluminum-nitride (FeAlN), or any other soft-magnetic material known to the art with a layer thickness of up to a few μm. The soft-magnetic layers 46 and 46' can be separated from each meandering electrical pickup 14 or 14' by a thin electrically-insulating layer (e.g. silicon nitride, silicon dioxide, a polymer, silicate glass or spin-on glass with a layer thickness of a few hundred nanometers). Deposition of the soft-magnetic layers 46 and 46' can be performed using evaporation, sputtering, or electroplating. Any magnetic force of attraction between the permanent magnets 18 and 18' and the soft-magnetic layers 46 and 46' can be substantially reduced by including one of the soft-magnetic layers 46 and 46' on each side of the shuttle 16.

The soft-magnetic layers 46 and 46' can also produce an increased damping of the shuttle 16 in the back-and-forth direction indicated by the double-headed arrow in Fig. 6 due to eddy currents generated therein. This damping can be reduced by reducing the thickness of the soft-magnetic layers 46 and 46' to less than a skin depth, by increasing an electrical resistivity of the layers 46 and 46', or by laminating a plurality of the soft-magnetic layers 46 and 46' together separated by thin (20 - 200 nm) electrically-insulating layers.

A plurality of MEM devices 10 can be batch fabricated on a common substrate 12 and electrically connected together in series or in parallel to provide an even higher electrical output power. By electrically connecting a plurality of the MEM devices 10 in parallel, a redundancy can also be provided to protect against the failure of certain of the MEM devices 10 thereby permitting a long operating life with unattended operation. The shuttles 16 can also be optionally interconnected via linkages to so that the shuttles 16 all operate in phase.

Figure 8 shows a plan view of a third example of the MEM apparatus 10. This example of the MEM apparatus 10 can be fabricated using bulk micromachining. The MEM apparatus 10 of Fig. 8 comprises a pair of substrates 50 and 50' stacked one

upon the other and attached together. Although this example will be described with reference to micromachining of silicon substrates 50 and 50', those skilled in the art will understand that the substrates 50 and 50' can comprise other micromachineable materials including semiconductors, glass, fused silica, quartz, ceramic, metal and metal alloys.

A first substrate 50, which is shown in the schematic plan view of Fig. 9, has a meandering electrical pickup 14 formed thereupon, with the meandering electrical pickup 14 being connected at each end thereof to at least one contact pad 24. This substrate 50 can be, for example, about 14 millimeters square. An optional soft-magnetic layer 46 can be provided on the substrate 50 beneath the meandering electrical pickup 14 as previously described with reference to Figs. 6 and 7. The location of the optional soft-magnetic layer 46 is indicated by the dashed rectangular outline in Fig. 9.

A photolithographically-defined mask (not shown) can be provided on the substrate 50 at the locations of a plurality of spacers 52 to be formed for precisely separating the shuttle 16 on the substrate 50' from the meandering electrical trace 14 on the substrate 50 when these two substrates 50 and 50' are attached together. Exposed portions of a topside of the substrate 50 not protected by the mask can then be etched downward (e.g. by reactive ion etching) to a predetermined depth of a few microns (e.g. 5 - 20 µm). In other embodiments of the MEM apparatus 10 schematically illustrated in Figs. 8 and 9, the spacers 52 can be formed from one or more layers of polycrystalline silicon (also termed polysilicon) which are deposited on the topside of the substrate 50 and patterned by an etching step. The polysilicon can be deposited by low-pressure chemical vapor deposition (LPCVD) at a temperature of about 580 °C.

A further etching step from either the topside or a backside of the substrate 50 can then be used to form a plurality of through-holes 54 which are useful for precisely

aligning the two substrates 50 and 50' prior to attaching the substrates together. For this purpose, a pin can be temporarily or permanently inserted through each through-hole 54 in the first substrate 50 and through another through-hole 54' formed in the second substrate 50'.

Etching of the through-holes 54 and 54' and etching through the substrate 50' as described hereinafter to form the shuttle 16, springs 20 and other elements on the substrate 50' can be performed using a deep reactive ion etch (DRIE) process such as that disclosed in U.S. Patent No. 5,501,893 to Laermer, which is incorporated herein by reference. The DRIE process for bulk micromachining of certain elements of the MEM apparatus 10 utilizes an iterative Inductively Coupled Plasma (ICP) deposition and etch cycle wherein a polymer etch inhibitor is conformally deposited as a film over the semiconductor wafer during a deposition cycle and subsequently removed during an etching cycle. The DRIE process for bulk micromachining produces substantially vertical sidewalls with little or no tapering for the through-holes 54 and 54' and for the various elements being formed on the second substrate 50'.

To electrically insulate the meandering electrical pickup 14 from the substrate 50, an electrically-insulating layer can be formed over the substrate 14. The electrically-insulating layer can comprise, for example, a layer of thermal oxide (about 600 nanometers thick) formed by a conventional wet oxidation process at an elevated temperature (e.g. 1050 °C for about 1.5 hours) and an overlying layer of low-stress silicon nitride (e.g. 800 nanometers thick) deposited using low-pressure chemical vapor deposition (LPCVD) at about 850 °C.

In Fig. 9, the meandering electrical pickup 14 can comprise a patterned layer of doped polysilicon or metal with a thickness, for example, of 1 - 2 μm and with a width of a few μm or more (e.g. 5 - 25 μm). As previously discussed, in certain embodiments of the MEM apparatus 10, a plurality of meandering electrical pickups 14 can be formed stacked one upon the other or interleaved, and interconnected in a

series or parallel arrangement. Although the meandering electrical pickup 14 is shown in Fig. 9 with a size about that of the plurality of permanent magnets 18 in Fig. 8, the meandering electrical pickup 14 can be extended over an entire range of back and forth travel of the shuttle 16 and permanent magnets 18 (i.e. from the pair of springs 20 at the top of Fig. 8 to the pair of springs 20 at the bottom of Fig. 8).

The second substrate 50' can be bulk micromachined to form the shuttle 16, springs 20 and other elements from the substrate material. This can be done using one or more DRIE steps as previously described. A first DRIE step can be used to form a plurality of slots 40 extending across a portion of the width of the shuttle 16 as shown in Fig. 8. A plurality of permanent magnets 18 can then be formed in the slots 18 as described hereinafter and covered with a lithographically-defined mask in preparation for a second DRIE step which is used to form the through-holes 54', the shuttle 16, springs 20, and other elements of the MEM apparatus 10 being formed from the substrate 50'. The shuttle 16 and springs 20 are generally of the same thickness as the substrate 50' (e.g. about 100 - 500 μm), with each spring 20 being, for example, 25 μm wide.

In Fig. 8, between the first and second DRIE steps, the permanent magnets 18 can be formed in the shuttle 16. This can be done as previously described by filling the slots 40 with a mixture of a rare-earth magnetic material 42 which is then hardened in place. By providing the permanent magnets 18 in a two-dimensional array of rows and columns as shown in Fig. 8, the structural stability of the shuttle 16 can be enhanced. Alternately, the MEM apparatus 10 of Fig. 8 can be fabricated with a plurality of permanent magnets 18 extending across a majority of the width of the shuttle 16 in a manner similar to that of the first example of the present invention in Fig. 1.

In yet other embodiments of the present invention, a soft-magnetic material (e.g. NiFe, FeCo or NiFeCo) can be deposited in every other slot 40 in each column

of slots 40 in Fig. 8, with the remaining slots being filled with the rare-earth material 42 (e.g. NdFeB or SmCo). The rare-earth permanent magnets 18 will then permanently magnetize the soft-magnetic material as previously described with reference to Figs. 2 and 3 to form a plurality of permanent magnets 18' which will have a north-south magnetic pole alignment that is opposite that of the rare-earth permanent magnets 18.

When the soft-magnetic material as described above is not used, an alternating north-south magnetic pole alignment can be provided in the MEM apparatus 10 of Fig. 8 by filling alternating rows of the slots 40 with two different rare-earth magnetic materials 42 to provide a plurality of alternating pairs of permanent magnets 18 with different Curie temperatures. The difference in Curie temperatures for the two different rare-earth magnetic materials 42 can then be used to alter an initial magnetization state of certain of the permanent magnets 18 having a lower Curie temperature while not substantially affecting the magnetization state of the remaining permanent magnets 18 having a higher Curie temperature. As an example, one permanent magnet in each alternating pair of the permanent magnets 18 can comprise a NdFeB rare-earth permanent magnet with a Curie temperature which can be in a range of about 310 - 365 °C; and the other permanent magnet in each alternating pair of the permanent magnets 18 can comprise a SmCo rare-earth permanent magnet with a Curie temperature T_C in a range of about 720 - 800 °C. Those skilled in the art will understand that many different material compositions are available for NdFeB and SmCo rare-earth permanent magnets, and that the Curie temperature will vary depending upon a particular material composition and whether the rare-earth permanent magnets 18 are bonded or sintered. Furthermore, the terms "NdFeB" and "SmCo" as used herein refer to rare-earth permanent magnets having the named elements therein, but which can contain up to about 10 % by weight of other elements.

A thermally-assisted magnetic field switching method, which utilizes the difference in Curie temperatures T_C for the alternating pairs of permanent magnets 18, can then be used to selectively magnetize the SmCo permanent magnets 18 with one north-south magnetic pole alignment and to selectively magnetize the NdFeB permanent magnets 18 with an opposite north-south magnetic pole alignment.

The thermally-assisted magnetic field switching method utilizes the relatively large difference in the Curie temperature T_C for the two different types of rare-earth permanent magnets 18 above. As the temperature of a permanent magnet is increased, the spontaneous magnetization of the permanent magnet will decrease and eventually vanish above a temperature called the Curie temperature T_C. Near the Curie temperature T_C, an energy barrier for switching the direction of magnetization of a permanent magnet can be significantly reduced while not destroying the spontaneous magnetization once the permanent magnet is cooled down to room temperature.

For the NdFeB permanent magnets 18, the Cure temperature is relatively low compared to the SmCo permanent magnets 18. Thus, when the NdFeB and SmCo permanent magnets 18 are both temporarily heated to a temperature within a range of 0 - 200 °C below the Curie temperature of the NdFeB permanent magnets, the magnetization of the NdFeB permanent magnets 18 can be switched with a lower external magnetic field than was initially used to magnetize the NdFeB and SmCo permanent magnets 18. In some instances, a magnetic field generated by the SmCo permanent magnets 18 can be sufficiently strong so as to switch the magnetization of the adjacent NdFeB permanent magnets 18 when substrate 50' containing the NdFeB and SmCo permanent magnets 18 is heated in the range of 0 - 200 °C below the Curie temperature of the NdFeB permanent magnets.

The NdFeB and SmCo permanent magnets 18 formed in the slots 40 can be initially magnetized all in the same direction using a high (≥ 30 kOe) external

magnetic field which can be continuous or pulsed. The substrate 50' can then be heated to a temperature in the range 0 - 200 °C below the Curie temperature for the NdFeB permanent magnets 18. This reduces a threshold for switching of the magnetization of the NdFeB permanent magnets 18 to align with an oppositely-directed external magnetic field, with the threshold being further reduced as the temperature is further increased in the above range (i.e. as the temperature becomes closer to the Curie temperature for the NdFeB permanent magnets 18). The oppositely-directed external magnetic field preferably has a magnetic field strength which is above the threshold for switching the north-south magnetic pole alignment of the NdFeB permanent magnets 18, while being below another threshold for switching the north-south magnetic pole alignment of a remainder of the permanent magnets 18 (i.e. the SmCo permanent magnets 18 which have a much higher Curie temperature of 720 - 800 °C). Each permanent magnet 18 in Fig. 8 can be, for example, 100 - 150 μm wide and about 1.5 millimeters long, with adjacent permanent magnets 18 being separated by a spacing of 100 μm. The energy product BH for each rare-earth permanent magnet 18 in Fig. 8 can be about 10 MGOe.

As an example, the NdFeB permanent magnets 18 with T_C = 350 °C can have an intrinsic coercivity H_{ci} which is 10 kOe at room temperature and which is reduced to 5 kOe at a temperature of 150 °C. The intrinsic coercivity H_{ci} is a measure of the magnetic field strength which is required to switch the north-south magnetic pole alignment for a particular permanent magnet. The SmCo permanent magnets 18 can have a value of H_{ci} = 17 kOe at room temperature, and 13 kOe at 150 °C. In this case, to switch the north-south magnetic pole alignment of the NdFeB permanent magnets 18 while not substantially altering the north-south magnetic pole alignment of the SmCo permanent magnets 18, the substrate 50' containing the NdFeB and SmCo permanent magnets can be heated in an oven to a temperature of 150 °C and the oppositely-directed external magnetic field can have a magnetic field strength of, for

example, 11 - 12 kOe. The substrate 50' can then be cooled down to room temperature with the oppositely-directed external magnetic field still applied, thereby resulting in the NdFeB and SmCo permanent magnets 18 having opposite north-south magnetic pole alignments.

It can also be possible to switch the magnetization of the NdFeB permanent magnets 18 using only the magnetic field produced by the SmCo permanent magnets 18. The SmCo permanent magnets 18 produce lines of magnetic flux ϕ which can loop around and pass through the NdFeB permanent magnets 18 in a manner similar to that shown in Fig. 3. At a temperature within the range of 0 - 200 °C below the Curie temperature of the NdFeB permanent magnets 18, the magnetic flux produced by the SmCo permanent magnets 18 can, in some instances, exceed the threshold for switching the magnetization state of the NdFeB permanent magnets 18. In this case, the NdFeB and SmCo permanent magnets 18 can be initially magnetized with the same north-south magnetic pole alignment using an external magnetic field as described above. The substrate 50' containing these permanent magnets 18 can then be heated to a temperature in the range of 0 - 200 °C below the Curie temperature of the NdFeB permanent magnets 18 so that the magnetic field strength provided by the SmCo permanent magnets 18 incident on the NdFeB permanent magnets 18 exceeds the threshold value of the intrinsic coercivity H_{ci} required to switch the north-south magnetic pole alignment of the NdFeB permanent magnets 18 while not switching the remaining SmCo permanent magnets 18. The exact value of the temperature to which the substrate 50' and permanent magnets 18 must be heated can be learned from practice of the present invention. After the polarity of the NdFeB permanent magnets 18 has been switched, the substrate 50' can be cooled back down to room temperature.

A soft-magnetic plate 220 having a Curie temperature higher than that of the NdFeB permanent magnets 18 can optionally be located on one or both sides of the

substrate 50' to improve coupling of the magnetic field from the SmCo permanent magnets 18 into the NdFeB permanent magnets 18 as shown in Fig. 11B. This location of the soft-magnetic plate 220 proximate to one or both poles of the SmCo permanent magnets 18 enhances the oppositely-directed magnetic field produced by the SmCo permanent magnets 18 within the NdFeB permanent magnets 18 by channeling the lines of magnetic flux ϕ in a manner similar to that shown in Fig. 7. Once the substrate 50' has been cooled back down to room temperature, the soft-magnetic plate 220 can be removed.

Although this thermally-assisted magnetic field switching method above has been described in terms of switching the north-south magnetic pole alignment of the NdFeB permanent magnets 18 prior to forming the completed MEM device 10 as shown in Fig. 8, this method can also be used after assembly of the completed MEM device 10. In this case, the magnetic field produced by the SmCo permanent magnets 18 can be enhanced at the locations of the NdFeB permanent magnets 18 by any soft-magnetic layer 46 located in the device 10 and/or by passing a pulsed or continuous electrical current through the meandering electrical pickup 14 to produce an additional pulsed or continuous magnetic field which is additive to the magnetic field produced by the SmCo permanent magnets 18.

An alternate method can also be used when the rare-earth permanent magnets 18 in the example of Fig. 8 all have the same or a different material composition. This method is described hereinafter with reference to Figs. 10A - 10C which show schematic cross-section views of a portion of the substrate 50' with the permanent magnets 18 formed in the slots 40. In Fig. 10A, all the permanent magnets 18 (e.g. comprising NdFeB, or alternately comprising NdFeB and SmCo) can be initially magnetized in the same direction as indicated by the vertically-pointing arrows. As described previously, this can be done using an external magnetic field having a magnetic field strength of ≥ 30 kOe (generally a pulsed magnetic field

oriented in the direction of the initial magnetization).

In Fig. 10B, a plate 200 comprising a non-magnetic material (e.g. a non-magnetic metal or metal alloy such as aluminum) with a plurality of elongate soft-magnetic regions 210 formed therein from a soft-magnetic material (e.g. NiFe, FeCo or NiFeCo) can be placed in contact with one or both major surfaces of the substrate 50', with each elongate soft-magnetic region 210 being aligned with every other permanent magnet 18. Each plate 200 can have lateral dimensions substantially equal to the substrate 50', and can further include a pair of through-holes (not shown) at the same locations of the through-holes 54' in the substrate 50' so that the plate 200 can be precisely aligned to the substrate 50' using a plurality of pins. The plate 200 and soft-magnetic regions 210 can be formed, for example, by LIGA by separately electroplating the non-magnetic material and the soft-magnetic regions 210, or alternately by etching or machining a plurality of slots at the locations of the soft-magnetic regions 210 and then filling in the slots with a soft-magnetic material (e.g. NiFe, FeCo or NiFeCo), for example, by electroplating. Any of the soft-magnetic material extending beyond the slots can be removed using a polishing step. The resulting elongate regions 210 can be about the same width or wider than the permanent magnets 18 so that each elongate region 210 covers only a single permanent magnet 18. The soft-magnetic material used for the regions 210 should preferably have a Curie temperature which is higher (e.g. by at least 100 °C) than that of the NdFeB rare-earth permanent magnets 18, and should also preferably be capable of providing a relatively high magnetic flux density in order to concentrate the external magnetic field H_{EX}.

With each plate 200 in place on the substrate 50', the plate(s) 200 and substrate 50' can be temporarily heated to a temperature near the Curie temperature of the permanent magnets 18 (e.g. about 150 - 300 °C for NdFeB permanent magnets 18) in the presence of a pulsed or continuous external magnetic field, H_{EX},

which is directed opposite the north-south magnetic pole alignment of the permanent magnets 18. Each soft-magnetic region 210 concentrates the external magnetic field, H_{Ex}, at the locations of every other permanent magnet 18 to provide a magnetic field strength which is above a threshold for switching the north-south magnetic pole alignment for the permanent magnets 18 superposed with the soft-magnetic regions 210. For the permanent magnets 18 not superposed with the soft-magnetic regions 210, the magnetic field strength of the external magnetic field is maintained below the threshold for switching the north-south magnetic pole alignment of these permanent magnets 18 so that they retain their initial magnetization state. It should be noted that the threshold for switching the alignment is the same for each NdFeB permanent magnet 18, but the magnetic field strength is different for the various NdFeB permanent magnets 18 depending on whether or not a particular NdFeB permanent magnet 18 is superposed with the soft-magnetic regions 210. The NdFeB permanent magnets 18 superposed with the soft-magnetic regions 210 experience a higher magnetic field strength and are switched in polarity; whereas the remaining NdFeB permanent magnets 18 not superposed with the soft-magnetic regions 210 are not switched in polarity due to a lower magnetic field strength at the locations of these permanent magnets 18. Furthermore, the flux lines from the soft-magnetic regions 210 reduce the net magnetic field strength in the permanent magnets 18 that are not superposed therewith.

The external magnetic field, H_{Ex}, can be maintained in place as the substrate 50' and each plate 200 are cooled down to room temperature. The result is an alternating north-south magnetic pole alignment for the plurality of permanent magnets 18 after removal of each plate 200.

Another alternative method which can be used to change the north-south magnetic pole alignment of certain of the permanent magnets 18 when the permanent magnets 18 all have the same rare-earth composition (e.g. NdFeB) or

different rare-earth compositions (e.g. with one-half of the magnets 18 comprising NdFeB, and with the remaining magnets 18 comprising SmCo) is described hereinafter with reference to Figs. 11A - 11C. In Fig. 11A, all the permanent magnets are initially aligned in the same direction using an external magnetic field as previously described. In Fig. 11B, a soft-magnetic plate 220 (e.g. comprising NiFe, FeCo or NiFeCo with a Curie temperature which is generally ≥ 400 °C and preferably ≥ 700 °C) with a meandering electrical conductor 230 is placed proximate to or against one or both major surfaces of the substrate 50'. The meandering electrical conductor 230 can be located in a plurality of slots 240 formed in the soft-magnetic plate 220, with the slots 240 being interconnected or open at each end and having the same spacing as the permanent magnets 18. The meandering electrical conductor 230 can be formed in the slots 240 or provided as insulated wire which is press fit therein. Through-holes (not shown) can be provided in each plate 220 for alignment with the through-holes 54' in the substrate 50', and to pin the assembly of the substrate 50' and plates 220 together.

The assembly can then be placed in an oven (not shown) and heated to a temperature which is in a range of 0 - 200 °C below the Curie temperature of the NdFeB rare-earth permanent magnets 18. A pulsed or direct current (dc) electrical current from a power supply (not shown) can then be passed through the conductor 230 to generate an external magnetic field sufficiently strong to switch the magnetic pole alignment of every other permanent magnet 18 as shown in Fig. 11B. The assembly can then be cooled down to room temperature with the external magnetic field applied to produce the north-south magnetic pole alignment shown in Fig. 11C.

When certain of the permanent magnets 18 in Figs. 11A - 11C comprise SmCo, then the external magnetic field produced by the conductor 230 and plate 220 is preferably aligned with the SmCo permanent magnets 18 so that the SmCo permanent magnets will generate additional lines of magnetic flux ϕ to assist in

switching the north-south magnetic pole alignment of the NdFeB permanent magnets 18.

Once the permanent magnets 18 have been formed in the substrate 50' and magnetized with an alternating north-south magnetic pole alignment, a photolithographically-defined mask can be provided over the substrate 50' and over the permanent magnets 18 with openings in the mask at the locations wherein the substrate 50' is to be etched using the second DRIE step described above. The second DRIE step etches completely through the substrate 50' to form the shuttle 16 and springs 20 from portions of the substrate 50'.

Additionally, the second DRIE step can be used to form a plurality of optional springs 56 which can be used to redirect the motion of the shuttle 16 when the shuttle 16 comes into contact with the springs 56. The springs 56 help to conserve momentum of the shuttle 16 and attached permanent magnets 18 to provide a relatively large back and forth movement of the shuttle 16 and magnets 18 while preventing the shuttle 16 from coming into direct contact with the substrate 50'. A plurality of optional stops 58 can also be formed in the substrate 50' as shown in Fig. 8 to further limit motion of the shuttle 16 and dampening springs 56 beyond a certain point. The dampening springs 56 can be, for example, 500 - 1000 μm long with a width of about 25 - 50 μm and a thickness equal to that of the substrate 50'.

In Fig. 8, the two substrates 50 and 50' can be attached together to complete the MEM apparatus 10. This can be done, for example, using an adhesive (e.g. epoxy), solder, or diffusion bonding, with a plurality of pins being inserted into the through-holes 54 and 54' to precisely align the two substrates 50 and 50'.

In other embodiments of the present invention, a pair of substrates 50 as shown in Fig. 9 can be sandwiched about the substrate 50' of Fig. 8 to provide a meandering electrical pickup 14 on each side of the shuttle 16 to provide an increased electrical output power or voltage signal. To facilitate the attachment of external wires to the

contact pads 24 in this case, a plurality of cutouts 60 can be formed in each substrate 50 during the DRIE step used for etching the through-holes 54 to provide access to the contact pads 24 when a pair of the substrates 50 are sandwiched about the substrate 50'.

Each MEM device 10 described herein can be hermetically packaged at ambient pressure or under a reduced pressure or vacuum to reduce a viscous damping on the movement of the shuttle 16 due to the ambient pressure.

Although the MEM apparatus 10 has been described as being fabricated by LIGA or micromachining, other embodiments of the MEM apparatus 10 can be fabricated using electrical discharge machining (EDM) as known to the art. Furthermore, in certain embodiments of the present invention, the permanent magnets 18 can be formed in the shuttle 16 by electroplating.

The methods for forming the plurality of permanent magnets with different north-south magnetic pole alignments have been described heretofore in terms of heating to a temperature in the range of 0 - 200 °C below the Curie temperature of the NdFeB permanent magnets 18, or whichever type of permanent magnet 18 has the lower Curie temperature when two different types of permanent magnets 18 are used in the MEM apparatus 10. When two different types of permanent magnets 18 are used in the MEM apparatus 10, the methods described heretofore for providing two different north-south magnetic pole alignments can be extended to heat the permanent magnet 18 having the lower Curie temperature to a temperature that is above that Curie temperature but still well below the Curie temperature of the other type of permanent magnet 18 having the higher Curie temperature.

As an example, when the two types of permanent magnets 18 comprise NdFeB with a Curie temperature in the range of 310 - 365 °C and SmCo with a Curie temperature in the range of 720 - 800 °C, heating the two types of permanent magnets 18 to a temperature above the Curie temperature of the NdFeB permanent

magnets 18 will permanently destroy an initial magnetism in the NdFeB permanent magnets 18 but will not substantially alter either the initial magnetism or the north-south magnetic pole alignment of the SmCo permanent magnets 18 which have a much higher Curie temperature. Thus, the two types of permanent magnets 18 can be initially magnetized with the same north-south magnetic pole alignment. The NdFeB and SmCo permanent magnets 18 can then be heated to a temperature in the range of 0 - 100 °C above the Curie temperature of the NdFeB permanent magnets 18 thereby destroying the initial magnetism in the NdFeB permanent magnets 18 and rendering them paramagnetic. The above temperature range to which the NdFeB and SmCo permanent magnets 18 are heated is still several hundred degrees below the Curie temperature of the SmCo permanent magnets 18 so that the initial magnetism in the SmCo permanent magnets 18 will not be appreciably affected by the heating. The NdFeB and SmCo permanent magnets 18 can then be cooled down to room temperature in the presence of an external magnetic field H_{Ex} as previously described with reference to Figs. 10A - 10C having a magnetic field strength which is below the intrinsic coercivity H_{ci} of the SmCo permanent magnets 18, or in the presence of the magnetic field from the SmCo permanent magnets 18, or both. Upon cooling down below the Curie temperature of the NdFeB permanent magnets 18, the NdFeB permanent magnets 18 will once again become ferromagnetic and will be remagnetized with a north-south magnetic pole alignment that is opposite that of the SmCo permanent magnets 18.

The matter set forth in the foregoing description and accompanying drawings is offered by way of illustration only and not as a limitation. The actual scope of the invention is intended to be defined in the following claims when viewed in their proper perspective based on the prior art.